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Electrical Engineering Research Laboratory
The University of Texas
Austin, Texas

Report No. 6-53 31 May 1963

CONSIDERING FOREST VEGETATION AS AN IMPERFECT DIELECTRIC SLAB

by
D. J. Pounds
A. H. LaGrone

Contract AF 19(604)-8038
Project 4603

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

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ABSTRACT

A method for representing a grove of trees by an imperfect dielectric slab is developed and illustrated. The method considers leaves as conducting bodies and bark and wood as dielectric bodies using artificial dielectric and dielectric mixture theory to compute the real part of the dielectric constant of the proposed slab. The imaginary part of the dielectric constant of the slab is computed from measured attenuation data. The method is illustrated using data from a real forest to compute the characteristics of an imperfect dielectric slab.

I. INTRODUCTION

It is well known that trees surrounding a receiving antenna have a decided effect on received signal strength at frequencies above approximately 30 megacycles per second. These effects are known qualitatively, but little has been done to give them a quantitative value. Quantitative information on the signal loss due to trees near the antenna would be valuable for selecting an optimum receiver site, computing the effects of a large forest on wave propagation, finding the optimum antenna height at a given location, the effect of a forest on the coverage area of television stations, and other problems. Thus, the problem in this study is to develop an approximate mathematical model of a grove of trees for use in theoretical calculations of field strength in the vicinity of the grove of trees.

One approach to the problem is to represent the grove of trees by a random distribution of short conductors and dielectric bodies from which the dielectric constant is computed. The attenuation is then determined from loss measurements. This is the approach adopted for this study.

First, the two principal tree types and some of the principal forest types in the United States are considered. They are located and described in terms of physical characteristics such as the names and description of major species including size and appearance. A

general description of the foliage, including such things as shape, size and some variations from species to species is presented.

Second, a statistical description of a fully stocked (moderately dense) even-aged forest stand is presented. These statistics include such things as the number of trees per acre, average diameter at breast height, basal area per acre, average heights, estimated or measured volumes of wood and bark per acre as a function of age and perhaps the characteristics of the site. These data are used in the synthesis of the dielectric slab model.

Third, the electrical properties of wood, bark, and leaves are reported. They are measured or estimated from the physical structure and moisture content of the subject. Consideration is given to such factors as frequency dependence of the dielectric properties and variations in the moisture content of the wood.

Fourth, methods for synthesizing the electrical properties of wood, bark, leaves, and air into the dielectric properties of an imperfect dielectric slab are derived.

Fifth, the method of calculation is illustrated by an example followed by a summary.

The dielectric slab concept is adopted because of the simplicity of application and the availability of a suitable program for calculation by means of a digital computer.

II. GENERAL REMARKS ON FORESTS

A forest is a large area of land covered by a moderate to dense growth of trees. A forest may or may not have underbrush. Some forests, for example, do not even have grass growing under the trees.

A tree is a "woody perennial, seed-bearing plant"[1] "which at maturity is 20 feet or more in height, with a single trunk, unbranched for at least several feet above the ground and having a more or less definite crown."[2] This definition cannot be taken as absolute but only as a guide. For example, some willow trees have multiple stems while many trees do not reach 20 feet in height under adverse conditions.

In this study, a tree is considered as made up of three principal components - wood, bark, and leaves. A number of components are neglected by such a division. These include the roots below the ground, the buds, flowers, fruit, and seed normally found above ground, and the cambium or growing layer between the wood and bark. It is also necessary to neglect some variations within the wood, bark, and leaves.

Foresters generally divide forest trees into two groups: (1) conifers or softwoods, and (2) broadleaf trees or hardwoods. There are some minor exceptions to the above classifications but they are insignificant to this study. A survey of the literature, for example, shows that a few conifers exhibit some characteristics like broadleaf trees and vice versa. These two groups of trees generally differ in crown form, branching habits, and wood structure as well as leaf shape.

A. Conifers

Conifer is a common name foresters use instead of the scientific name gymnosperms. Conifer literally means cone bearing. The terms softwoods and evergreens are also used but these terms are misleading since some conifers are not evergreen and some softwood lumber is harder than the lumber of some hardwoods.[3]

Most conifers tend to have conically shaped crowns. In the forest, however, competition forces the crowns to be more cylindrical in shape, smaller in horizontal dimensions, and the base of the crown to be located at a greater height above the ground.

The conifers generally have small, relatively short, nearly horizontal branches. These branches are usually of small diameter compared to the trunk and do not significantly affect the trunk's diameter; i.e., the diameter above and below a given branch is approximately the same. This structural form means that almost all the wood volume is present in the stem.[5] Probably more than 80% of the wood volume is contained in the stem of large trees.

Conifers are resinous trees with needle- or scale-like leaves. The leaves are evergreen on most conifers but certain cypress, tamarack, and larch shed their leaves in the Fall. The leaves may be borne singly or in clusters.[3]

The seed of most conifers are, as the name implies, borne in cones, but the junipers bear a berrylike seed, and the yew a fleshy

scarlet disk. The conifers include cypresses, pines, hemlocks, spruces, firs, cedar, tamaracks or larches, pinyons, yews, junipers, the giant sequoias and redwoods.[3]

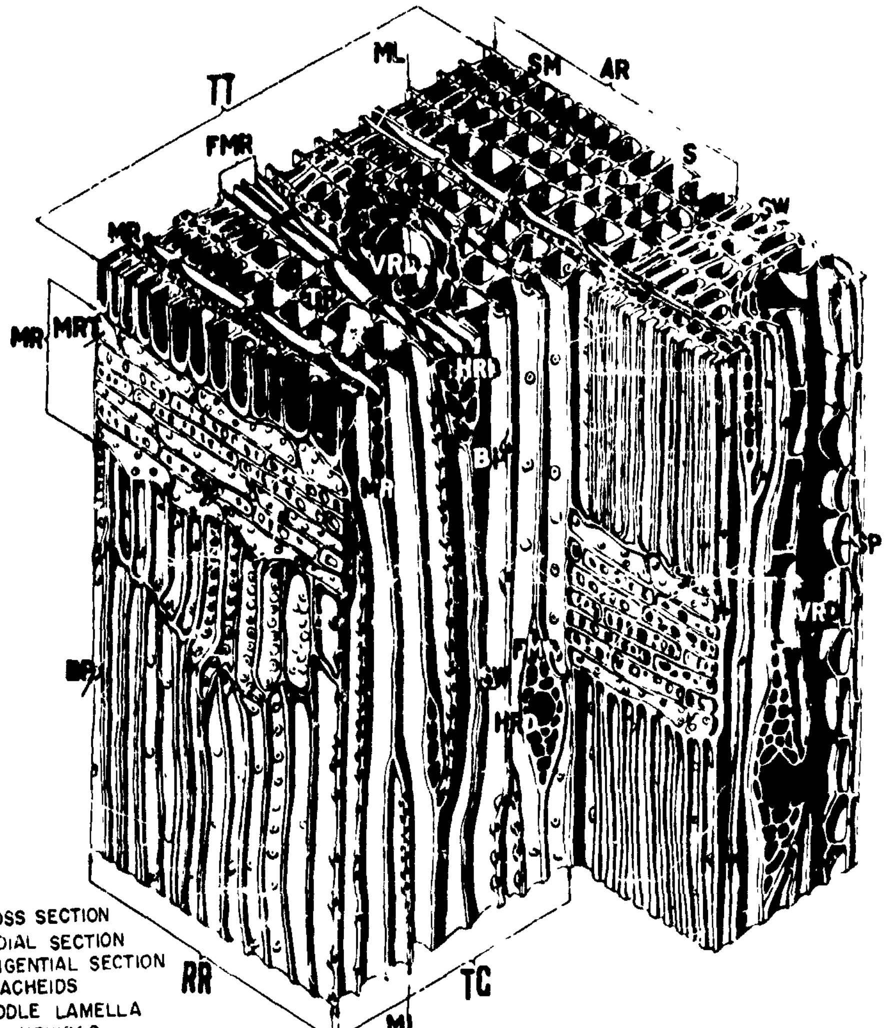
The cellular structure of a conifer wood sample is shown in Figure 1. Up to 90% of the volume may be occupied by "vertically oriented, thick-walled dead cells (of cellulose) varying in length from 0.5 to 15 millimeters."[6] Transversely, oriented wood rays are also present. Note from the figure that large, vacant volumes are present which are filled in the tree by gases and water.[6] All of these have an important effect in determining the dielectric properties of the conifer wood.

B. Hardwoods

Foresters use the term "hardwood" instead of the scientific name angiosperms even though palms and yuccas are angiosperms but not hardwoods. Hardwoods are also called broadleaf trees and deciduous trees but the term deciduous can lead to confusion because a few hardwoods have evergreen leaves.[3]

Generally, hardwood trees tend toward spherical, ellipsoidal and cylindrical crowns.[4] Their crowns tend to be proportionally larger in horizontal dimensions than the conifers. In the forest, competition causes the crowns to be narrower than shade tree hardwood profiles indicate.

The different crown shape covers a different branching structure in the hardwood. The branches of hardwood trees are relatively



TT - CROSS SECTION
RR - RADIAL SECTION
TG - TANGENTIAL SECTION
TR - TRACHEIDS
ML - MIDDLE LAMELLA
S - SPRINGWOOD
SM - SUMMERWOOD
AR - ANNUAL RING
MR - WOOD RAY
FMR - FUSIFORM WOOD RAY
HRD - SIMPLE PIT
BP - BORDERED PIT

US FOREST SERVICE, FOREST PRODUCTS LAB PHOTOGRAPH

CELLULAR STRUCTURE OF A SAMPLE OF CONIFER WOOD

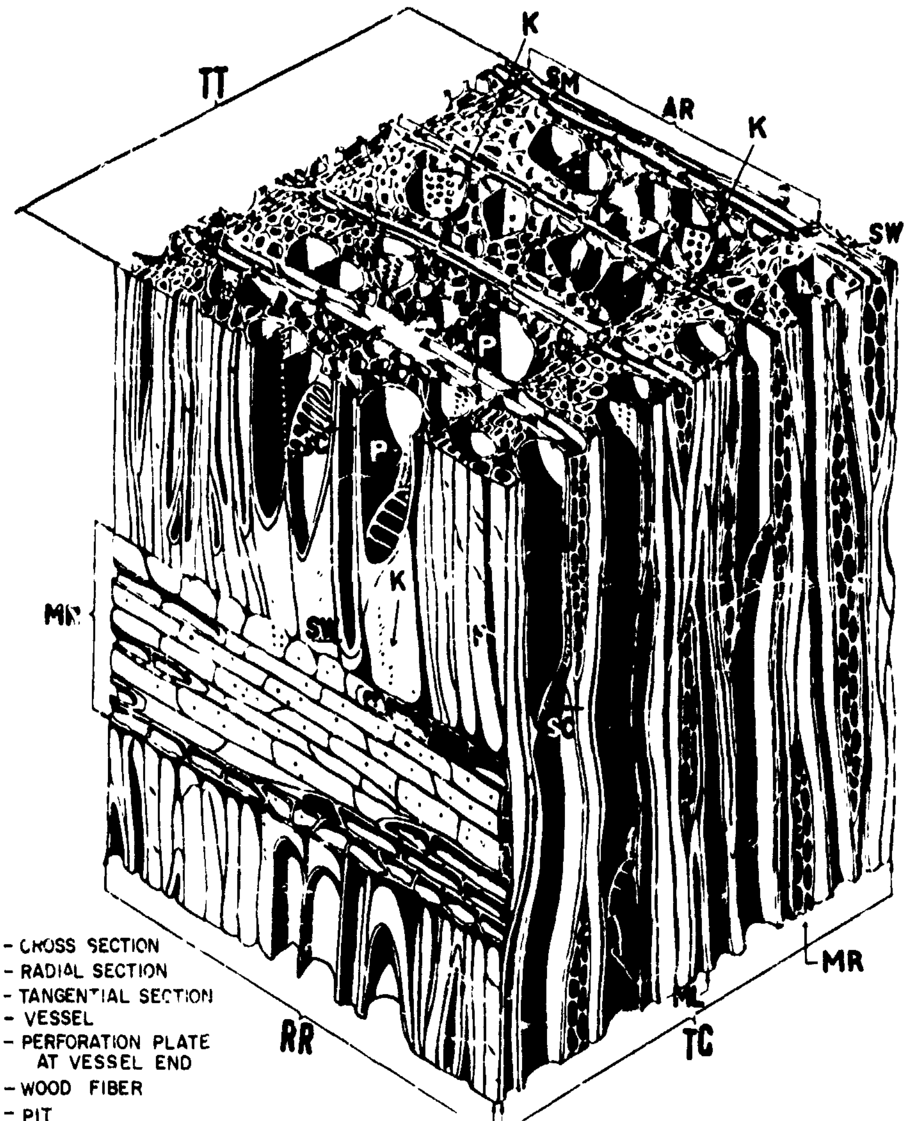
FIG. 1

large compared to the trunk. Thus, often the stem is considerably smaller above a branch or circle of branches than below the branch. Near the top, heavy branching causes the stem to lose in size rapidly.[5] In many species, the branches form an acute angle with the trunk going upward as well as outward. These branching habits add up to a smaller percentage of the total wood being found in the stem of hardwoods.[5]

Hardwood trees are non-resinous and have broad leaves. The leaves may be simple or compound, i.e., made up of leaflets. Most species shed their leaves in the fall, i.e., are deciduous. However, live oaks, magnolias, American holly, laurel oaks, redbay, laurel cherry, many small tropical and subtropical trees, and possibly a few other species have green leaves throughout the winter. The leaves of hardwood trees are net veined, the seeds are enclosed in a fruit, and the bark is distinct from the wood which has annual rings. The hardwoods include catalpa, dogwood, maples, ashes, box elders, buckeyes, walnuts, butternuts, pecans, hickories, mahogany, locusts, sassafras, mulberry, osage-orange, gums, sycamores, magnolias, bays, tupelos, persimmon, holly basswood, elm, hackberries, cottonwoods, poplars, birches, willows, cherries, beeches, chestnuts, oaks, alder, buckthorn, madrone chinquapin, and perhaps others.[3]

Wood structure of a hardwood is illustrated in Figure 2. Its structure is more complex than softwood structure. Most hardwoods contain vertically oriented tubes and vertically oriented wood fibers.

The chief function of the tubes is to conduct water, but some of the older tubes become blocked. Once again, a considerable volume of the wood is occupied by water and gases.[6]



TT - CROSS SECTION
RR - RADIAL SECTION
TG - TANGENTIAL SECTION
P - VESSEL
SC - PERFORATION PLATE AT VESSEL END
F - WOOD FIBER
K - PIT
MR - WOOD RAY
AR - ANNUAL RING
S - SPRINGWOOD
SM - SUMMERWOOD
ML - MIDDLE LAMELLA

U S FOREST SERVICE, FOREST PRODUCTS LAB PHOTOGRAPH

CELLULAR STRUCTURE OF A SAMPLE OF HARDWOOD WOOD

FIG 2

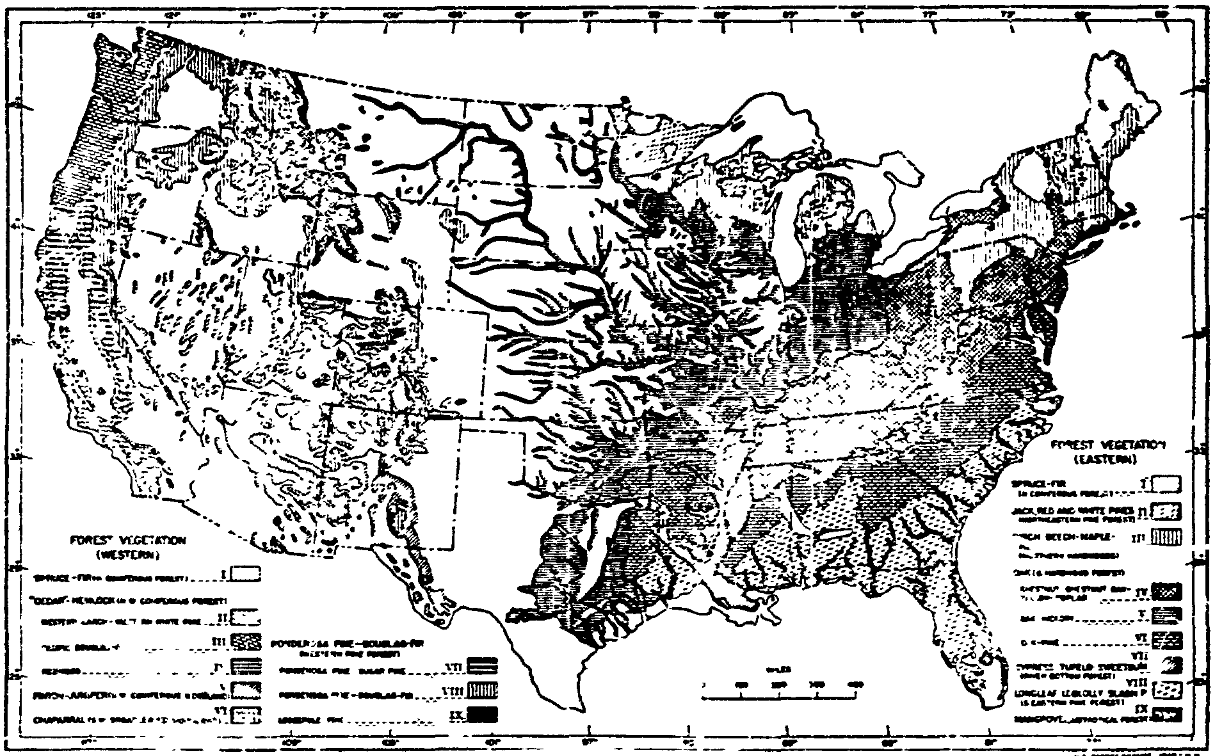
III. TYPES OF FORESTS

The original forests covered about 48% of the total area of the United States[7] but this amount has been reduced considerably by lumbering and clearing for agricultural and other purposes. There are 1,182 different kinds of forest trees in the original 48 states[8] of which, over 100 are of commercial importance. Many other species can be found in Hawaii and Alaska.

The forest classifications and locations used throughout this report are from Shantz and Zon,[7] who divide the natural forest vegetation into 12 regions and 18 subregions. (The areas specified as regions in this report were called subregions by Shantz and Zon.)

The western forest regions are spruce-fir, western white pine - western larch, Douglas-fir, redwood, pinyon-juniper, chaparral, ponderosa pine - sugar pine - incense-cedar, ponderosa pine - Douglas-fir, and lodgepole pine. The eastern forest regions are spruce-fir, northeastern pine, northern hardwood, chestnut-chestnut oak - poplar, oak-hickory, oak-pine, cypress-tupelo - sweetgum, southern pines, and mangrove.[7]

These regions may be located by use of the map (Figure 3) with more detailed data in Shantz and Zon.[7] This map is an adaptation of Shantz and Zon's original found in Forestry Handbook.[9]



U.S FOREST SERVICE, FOREST VEGETATION OF THE U.S 48

FOREST VEGETATION OF THE UNITED STATES

FIG. 3

IV. STATISTICAL DESCRIPTION OF FOREST

In order to approximate a forest by a dielectric slab it is necessary to know within reasonable limits how much of the overall volume represented by a forest is occupied by wood and bark and the number of leaves. This is necessary since the dielectric properties of wood, bark, leaves and air differ.

Information of this type is obtained from yield tables which predict the wood available from an acre of land fully stocked with trees. These tables normally give the "total" (or sometimes merchantable) cubic feet of wood in the <u>stems</u> of the trees on an acre of land. This yield is usually given as a function of age and site quality for a particular species of tree.

The yield tables serve the needs of the forester well but must be modified to include the wood and bark in the branches, tree top, and stump since these are important in this study. An estimate of the number of leaves must also be made since this data is not normally available.

It is beyond the scope of this paper to present volumes of bark, wood and leaf quantities for all important species, but an example will be presented to illustrate the methods used in compiling this information.

To clarify the data to be presented a few terms will be defined and discussed.

Yield tables, which form the basis of the data used in this study, are prepared for even-aged stands of one species or groups of species that are fully or normally stocked (fairly dense). Even-aged means that the members of the stand are of about equal age; that is, all started growing within the normal time for natural replanting. This may be one or more years.

The age of a tree is expressed in years. Age is usually determined by boring a sample out of a tree at breast height and counting the number of annual rings. The forester then adds the number of years that he estimates it took the tree to grow to breast height.

The diameter at breast height of a tree (d. b. h.) in inches is measured outside the bark at a point 4-1/2 feet above the ground. For elliptically shaped stems, the major and minor axis values are averaged. The average diameter at breast height in the tables is the d. b. h. of the tree of <u>average</u> <u>basal</u> <u>area</u>.

The number of trees per acre (N) is a count of all trees with a d. b. h. greater than a certain value selected by the investigator.

The basal area (A_b) per acre in square feet is the sum of the areas of all tree stems at breast height (larger than a certain d. b. h.) on an average acre of land fully stocked with trees. Each tree stem is considered as a circle for purposes of area calculations.

Dominant trees are those with crowns extending above the general level of the forest canopy, receiving full light from above and partly from the side; they are larger than the average trees in the stand and have crowns that are well developed though they may be somewhat crowded on the sides.

Codominant trees are those with crowns which form the general level of the forest canopy and receive full light from above but comparatively little from the sides; they are usually trees with medium-sized crowns that are more or less crowded on the sides.

Intermediate trees are those with crowns below, but still extending into the general level of the forest canopy, receiving a little direct light from above, but none from the sides; these trees usually have small crowns that are shaded on all sides.

Overtopped trees are those with crowns that are entirely below the general forest canopy and receive no direct light either from above or from the sides.[10]

The average height of the dominant and codominant trees (H_d) is the average of the heights (ground to tip) of only the dominant and codominant trees. The average height of all the trees (H_a) includes all four classes of the same approximate age. The H_a, for example, would omit a ten year old seedling in a fifty year old stand. Forest height (H_f) is a term coined for use in this paper and is an average of the average

height of the dominant and codominant trees and the average height of all the trees. Forest height, then, is an average of the two average heights as defined above. Forest height, as will be pointed out later, is also assumed to be the height of the imperfect dielectric slab being developed for use in signal strength calculations.

The volume of wood in cubic feet (V_w) is taken from the yield table. In some cases, the original values should be multiplied by an estimated correction factor in order to obtain the total wood volume on an acre. This correction factor is based on the structure of the tree and the parts of the tree not included in the volume reported in the yield table.

The bark volume in cubic feet (V_b) per acre is taken from the yield table (with estimated corrections as above) or estimated using experience gained from other species and various percentage values found in the literature.

Annual leaf fall (W_L) in pounds and number of leaves (N_L) per cubic meter are approximations made from meager data. These leaf estimates are based on a few reports on oven dry weight of the annual fall and the average live life of a leaf.

Per unit volumes of wood (v_w) and bark (v_b) are computed, taking the base volume to be that of a rectangular solid of 1?,5?? square feet base area and a height equal to the forest height.

A statistical description for loblolly pine is given in Table 1.

TABLE I

STATISTICAL DESCRIPTION OF A ONE-ACRE FULLY STOCKED STAND OF LOBLOLLY PINE
(Site Index = 90)

Age	H_d	H_a	N	A_b	dbh	V_w	V_b	W_{Lf}	H_f	V_s	v_w	v_b	N_L
Yrs.	Ft.	Ft.	No.	Ft^2	In.	$Ft.^3$	$Ft.^3$	Lbs.	Ft.	$10^6 Ft.^3$	$x 10^{-2}$	$x 10^{-4}$	
15	37	30	1210	114	4.2	1600	600	3540	34	1.503	.1064	3.992	1960
20	[illegible]	44	790	133	5.6	2300	790	3620	46	2.004	.1148	3.49[illegible]	1500
[illegible]	5[illegible]	54	54[illegible]	144	7.0	3100	800	3[illegible]80	56	2.439	.1271	3.280	1250
30	67	63	420	152	8.2	3350	900	3[illegible]20	65	2.831	.1360	3.179	1090
35	74	71	345	157	9.[illegible]	4600	900	3760	72	3.136	.1467	2.870	994
40	81	77	299	162	10.2	5200	1000	3800	79	3.441	.1511	2.906	[illegible]16
45	86	82	250	165	11.1	5700	1100	3840	84	3.650	.1552	3.014	872
50	[illegible]0	86	220	167	12.0	6150	1100	3880	88	3.833	.1584	2.870	[illegible]39
55	93	90	195	169	12.7	6450	1150	3920	92	4.[illegible]07	.1610	2.8[illegible]	811
60	96	93	180	171	13.4	6700	1150	[illegible]960	94	4.095	.1636	2.808	802
65	98	95	1[illegible]0	173	14.0	6950	1150	4000	96	4.182	.1652	2.750	793
70	100	97	150	174	14.6	7100	1200	4040	98	4.269	.1653	2.811	785
75	102	99	140	175	15.1	7250	1200	4080	100	4.356	.1664	2.755	777
80	103	100	135	176	15.6	7400	1200	4120	102	4.443	.1667	2.701	769

The first 8 columns are taken from U.S.D.A. Misc. Publication No. 50[1]

The leaf data is an estimate based on data by Metz[12,13] and information from other writers.

H_d - average height of dominant trees

H_a = average [illegible] of "all" trees

N = number [illegible]/acre

A_b = basal area/acre

dbh = 'average' diameter at breast height

V_w = volume of wood/acre

V_b = volume of bark/acre

W_{Lf} = leaf fall pounds/acre/year

H_f = forest height

V_s = volume of dielectric slab/acre

v_w = per unit wood (by volume)

v_b = per unit bark (by volume)

N_L = number of leaves/cubic meter

It should be remembered that the figures given in Table 1 are for fully stocked, even-aged pure stands with little or no underbrush. This may give some feel for understocked areas, however.

At the present time, it is not clear how to get the best estimates on understocked areas. One might assume that wood and bark per unit volumes are directly proportional to basal area or can perhaps be expressed as a function of basal area.

V. DIELECTRIC PROPERTIES OF WOOD

Wood has long been used as a dielectric material, i.e., dry wood or wood with a low moisture content. The moisture content is normally reported as a per cent of the oven dry weight of wood. Expressed mathematically

$$MC = 100 \left[\frac{W_{wet} - W_{dry}}{W_{dry}} \right] \tag{1}$$

where MC = moisture content in per cent (by weight)

W_{wet} = weight of the wood when "wet", i.e., before oven drying

W_{dry} = weight of wood when "oven dry"

The wood (i.e., seasoned lumber) used to build houses, furniture, etc., has a moisture content of approximately 6 to 24 per cent depending on the method of seasoning and the relative humidity where it is seasoned and used.[14] However, this study is concerned with living wood.

Wood which has just been cut is referred to as green wood. Green wood initially has the same weight, physical structure, and moisture content as living wood. Only the presence of growth processes distinguish the living wood. Therefore, it is reasonable to assume that green wood and living wood are electrically identical.

Moisture contents for green wood are available in Wood Handbook.[14] It is immediately obvious from studying this information that large quantities of water are present in the wood of a living tree.

Takeda[15] and Stamm[16,17] have suggested that the water present in timber be grouped in three classes:

(1) strongly bound water (moisture content roughly 0 to 5 per cent)

(2) weakly bound water or capillary absorbed water (moisture content roughly 5 to 30 per cent)

(3) nearly free water (moisture content greater than 30 per cent).

Reported dielectric constant curves seem to indicate that these classes change gradually from one to another.

Bound water is reported to have much longer relaxation time than free water[15] leading to a lower dielectric constant for wood at higher frequencies.

Wood definitely has anisotropic dielectric properties. The dielectric constant in a direction parallel to the long wood vessels (longitudinal) is considerably greater than along a radius of the tree trunk (radial), or tangent to the wood rings (tangential), or any other direction perpendicular to the wood vessels (transverse).

Skaar[18] explained the anisotropy as follows:

> The parallel-to-grain constant of wood [illegible] significantly greater than the corresponding perpendicular-to-grain constant. [illegible]ne reason for this difference may be resident in the ultimate structure of the cell wall

> The cellulose component of cell walls consists of chain molecules which are in parallel at intervals throughout their length and hence form crystallites. The long axes of the bulk of these crystallites are essentially parallel to the long axes of the cells of which they are a part, and hence they are parallel to the grain of the wood. On the sides of the chain molecules, hydroxyl groups and water molecules are so arranged that rotation or vibration may occur more readily in an electric field which is parallel to the crystallites than in one which is at right angles to them. The degree of the rotation of the molecule in an electric field contributes to its dielectric constant. This may explain the directional differences in the dielectrical constants as determined.

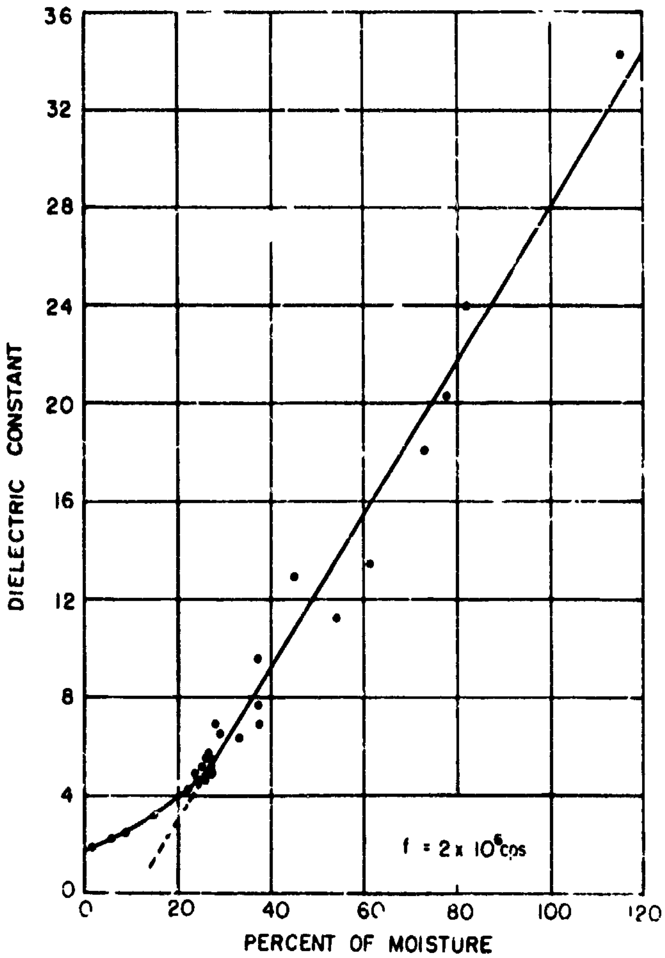
Since the media is anisotropic, the dielectric constant of wood to be used can be chosen only after consideration of the E field direction in the forest. Tree trunks can be considered (in most cases) to be vertical and perpendicular to the ground. Thus, for vertical polarization, the longitudinal dielectric constant is used. Similarly, for horizontal polarization, a transverse dielectric constant is used. Substitutions and estimates will be used where the required information is not available.

Shaar[18] reports that the dielectric constant of buckeye wood increases with moisture content (Figure 4). The measurements were made at 2 Mcps.

Hearmon and Burcham[19] report measurements of the dielectric properties of oak and Wych elm. Figure 5 is a plot of dielectric constant versus frequency, and Figure 6 gives the corresponding results for the loss tangent. Hearmon and Burcham report dielectric constants greater than 400 for low frequencies. These values seem somewhat high and out of line with those reported by other workers. They attribute their high values to "polarization effects caused by electrolytic conduction in the material."[19]

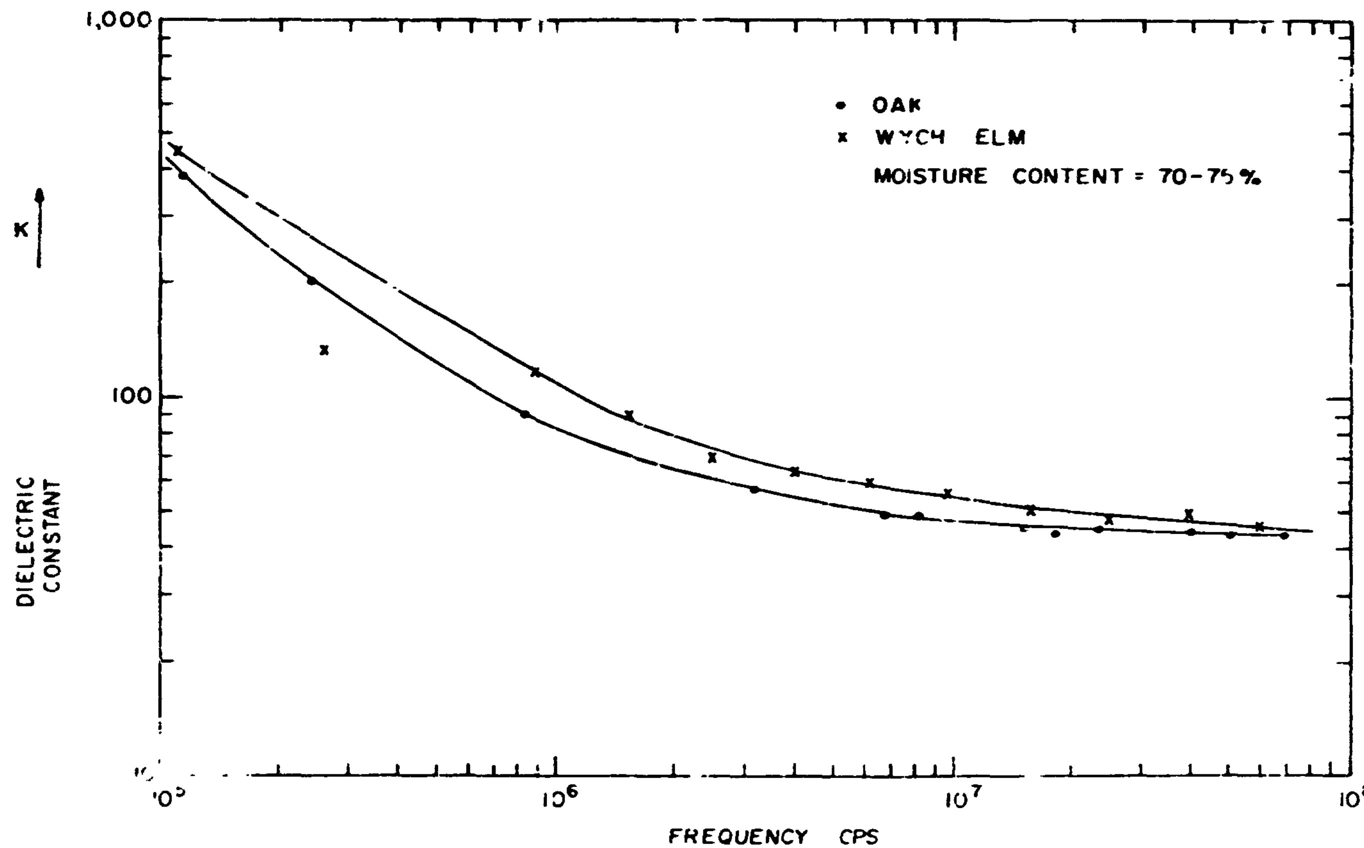
Trapp and Pungs[20] reported on the dielectric properties of a species of fir wood which is probably common in Germany. Figure 7 shows that the dielectric constant increases with moisture content. Figure 8 shows that the dielectric constant decreases with increasing frequency. Note that at high moisture contents and low frequencies, the dielectric constant of fir wood approaches the dielectric constant of water. Figures 9 and 10 give the corresponding loss tangent data which shows that green fir wood is a very lossy dielectric. In fact, at the lower frequencies the conduction current exceeds the displacement current so that it acts more like a conductor than a dielectric.

Takeda[15] made measurements on basswood which are of limited value to this study and are readily available in the literature.



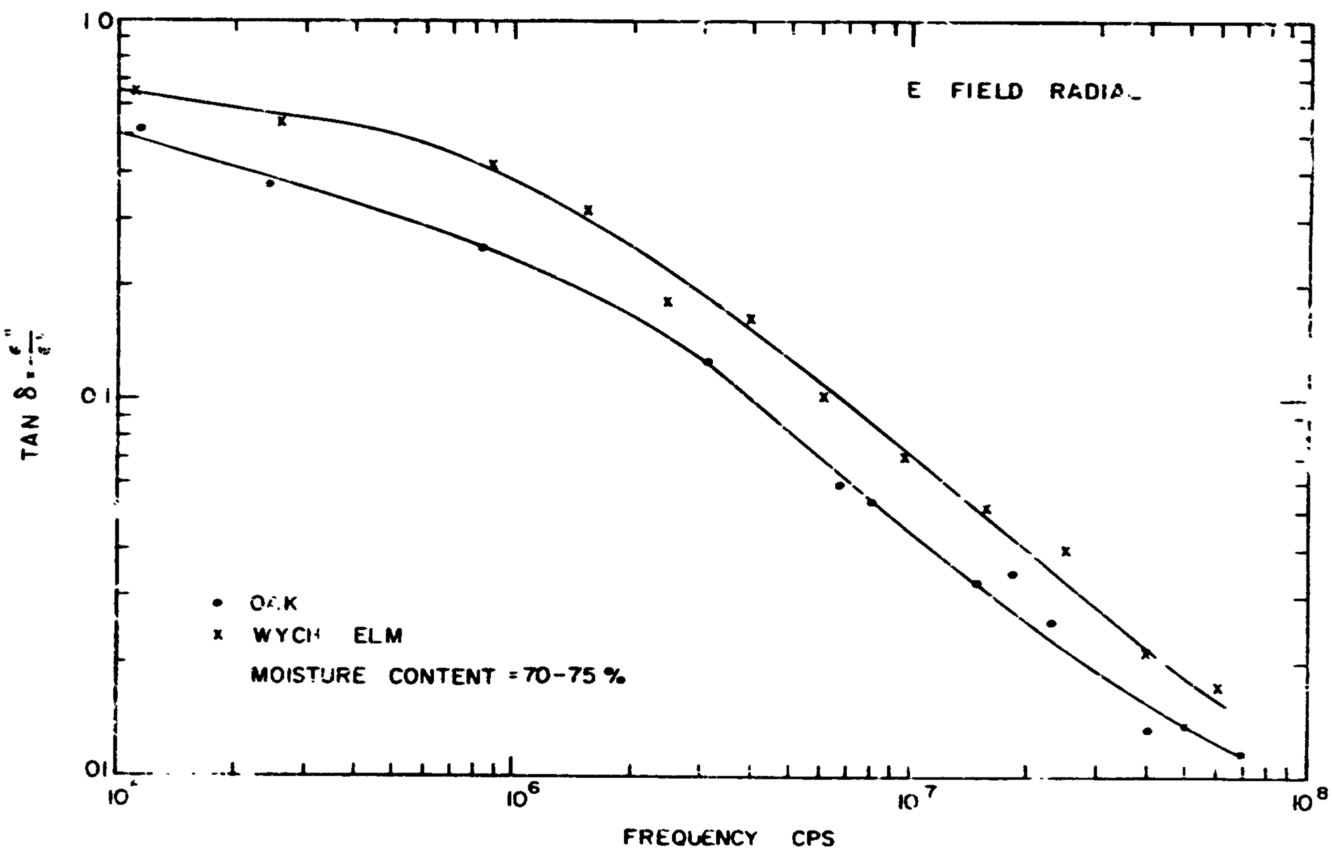
DIELECTRIC CONSTANT OF BUCKEYE WOOD

FIG [illegible]



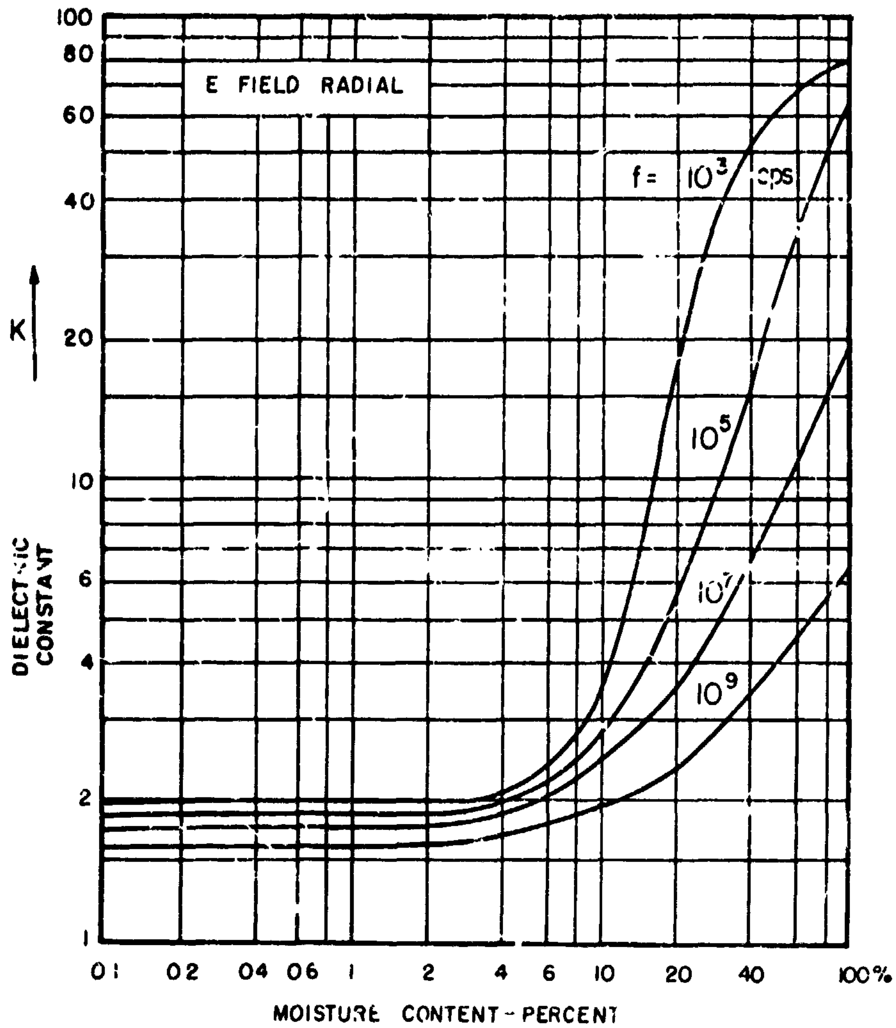
DIELECTRIC CONSTANT OF OAK AND WYCH ELM

FIG 5



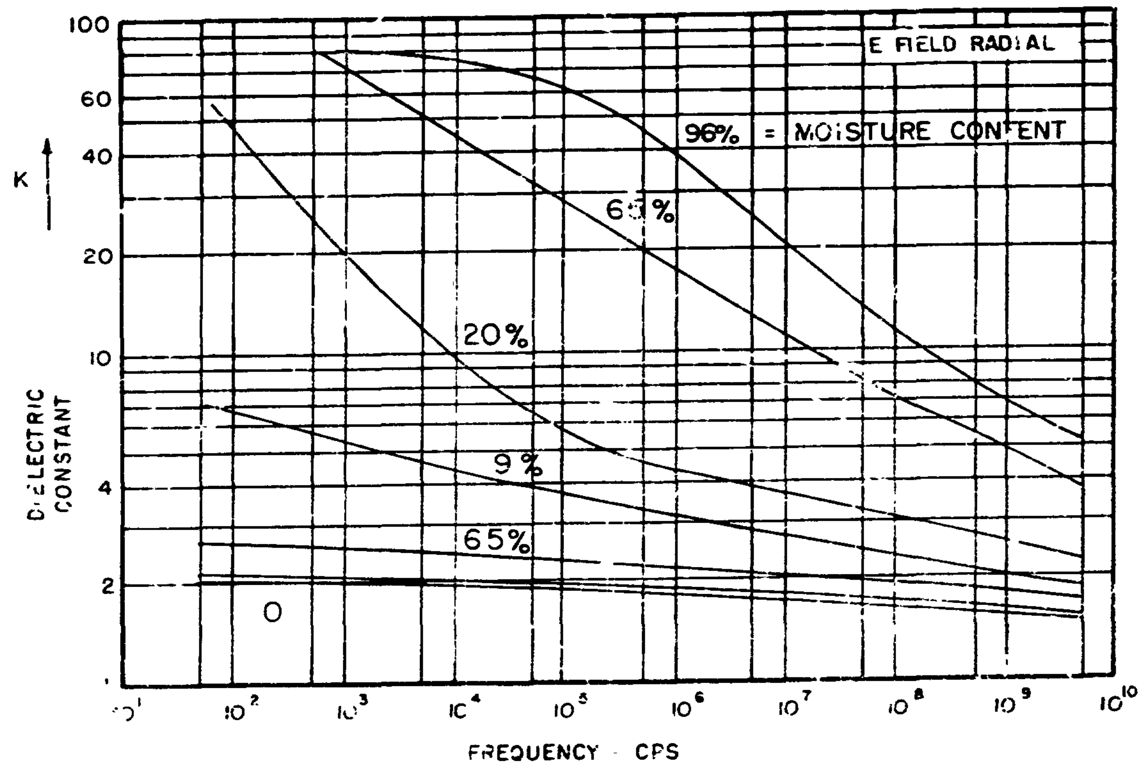
LOSS TANGENT OF OAK AND WYCH ELM

FIG. 6



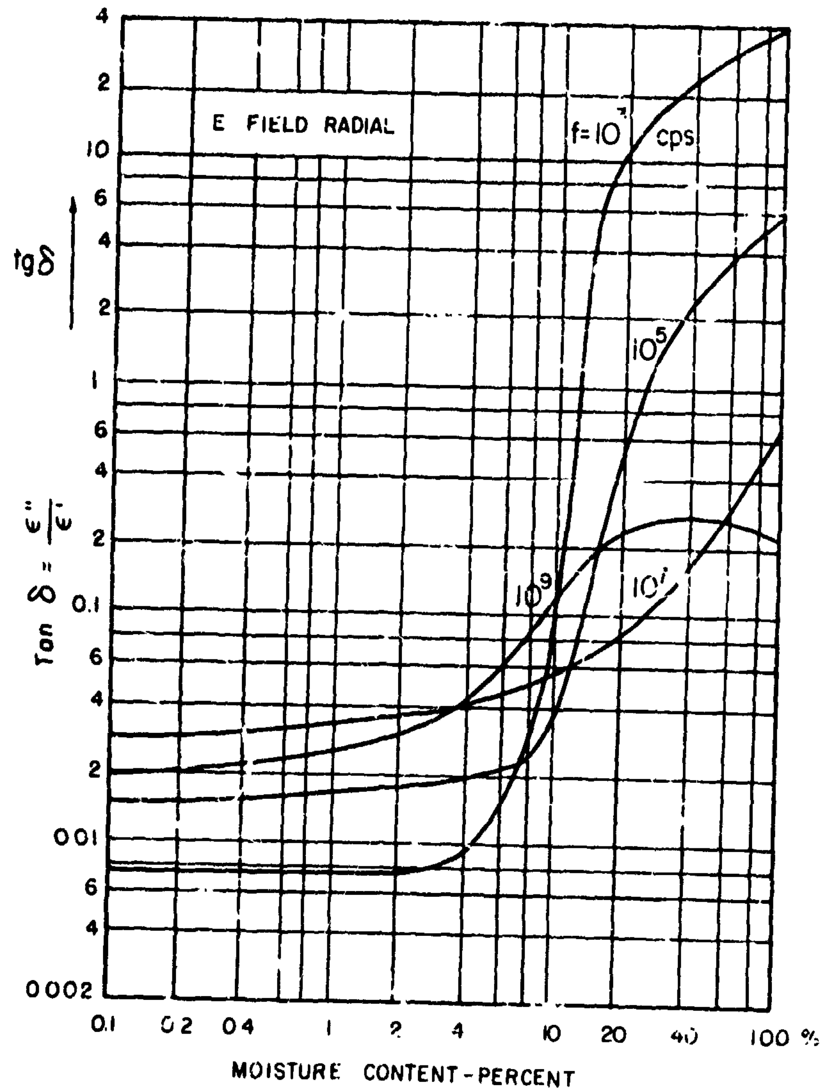
DIELECTRIC CONSTANT OF FIR WOOD AS A FUNCTION OF MOISTURE CONTENT

FIG 7



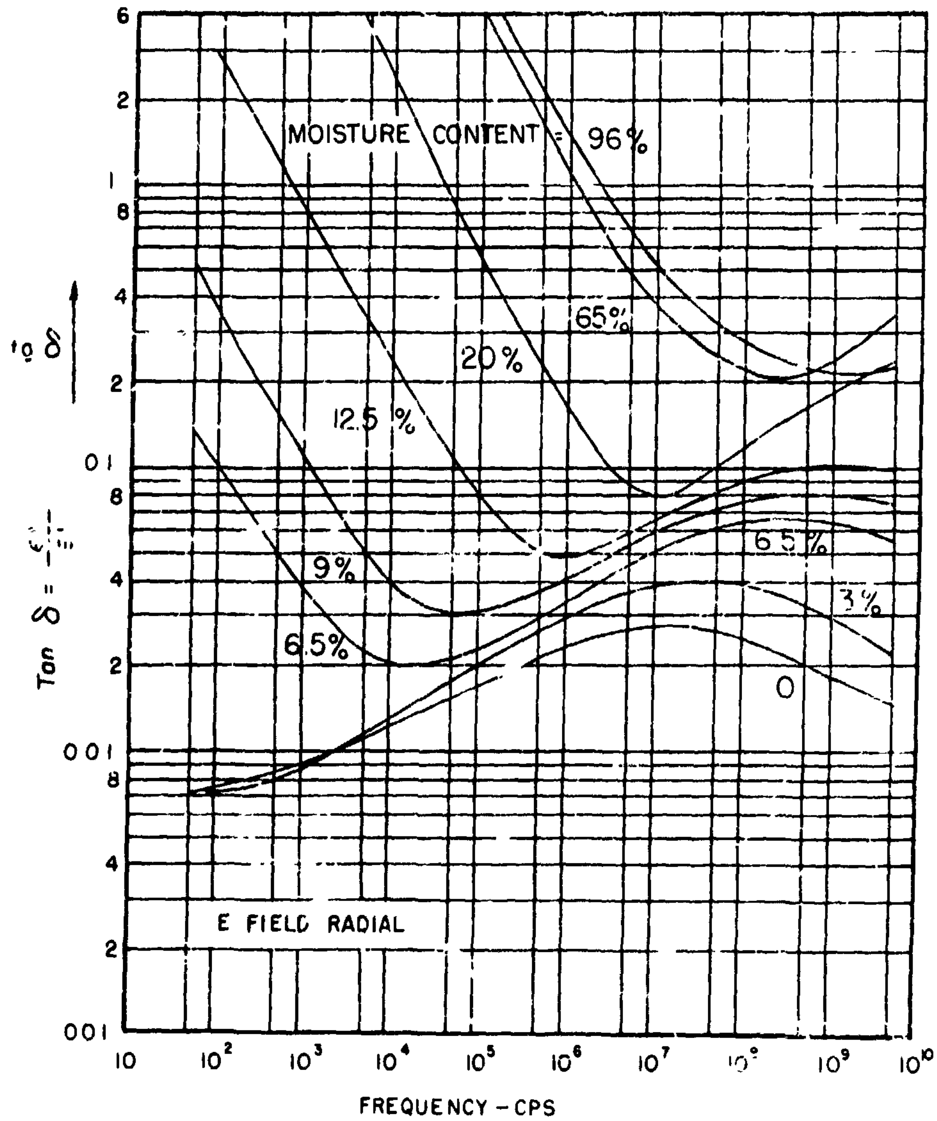
DIELECTRIC CONSTANT OF FIR WOOD AS A FUNCTION OF FREQUENCY

FIG 6



LOSS TANGENT OF FIR WOOD AS A FUNCTION OF MOISTURE CONTENT

FIG 9



LOSS TANGENT OF FIR WOOD AS A FUNCTION OF FREQUENCY

FIG 10

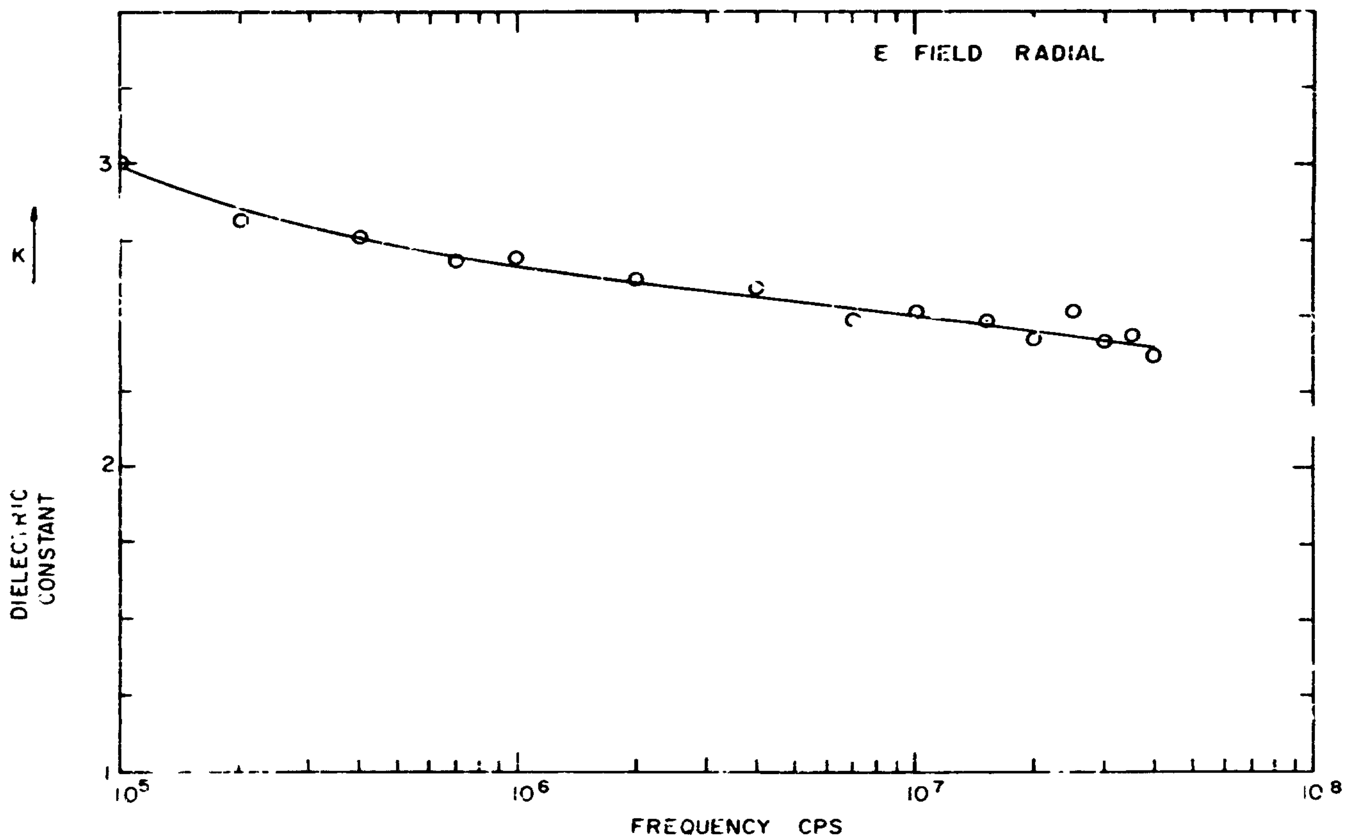
The data presented in detail in this section were not taken on the species of greatest interest in this study; however, the data indicate that the dielectric properties of green wood, whatever the species are primarily dependent on moisture content. The wood structure of conifers and hardwoods differs considerably, however, so it seems reasonable to use conifer data to estimate the dielectric properties where possible, of conifer woods rather than hardwood data. The wood dielectric data presently available are so incomplete that it cannot be said whether species to species variations among the conifers or among the hardwoods are significant.

A second possibility exists for the treatment of the stem and branches of trees in a forest in determining the electrical properties of the forest. The cambium layer, growth layer, contains a great deal of moisture in which there are many dissolved substances;[6] therefore, it probably has a relatively high conductivity. In this case, it is possible that the cambium layer effectively forms a conducting sheath around the wood parts of the trunk and branches. In such a case, the wood parts of the tree should be represented by conducting bodies of the same shapes. These shapes would be approximated by conducting solids of simpler geometry, such as cones, cylinders or paraboloids. This approach to the problem is not considered in this paper.

VI. DIELECTRIC PROPERTIES OF BARK

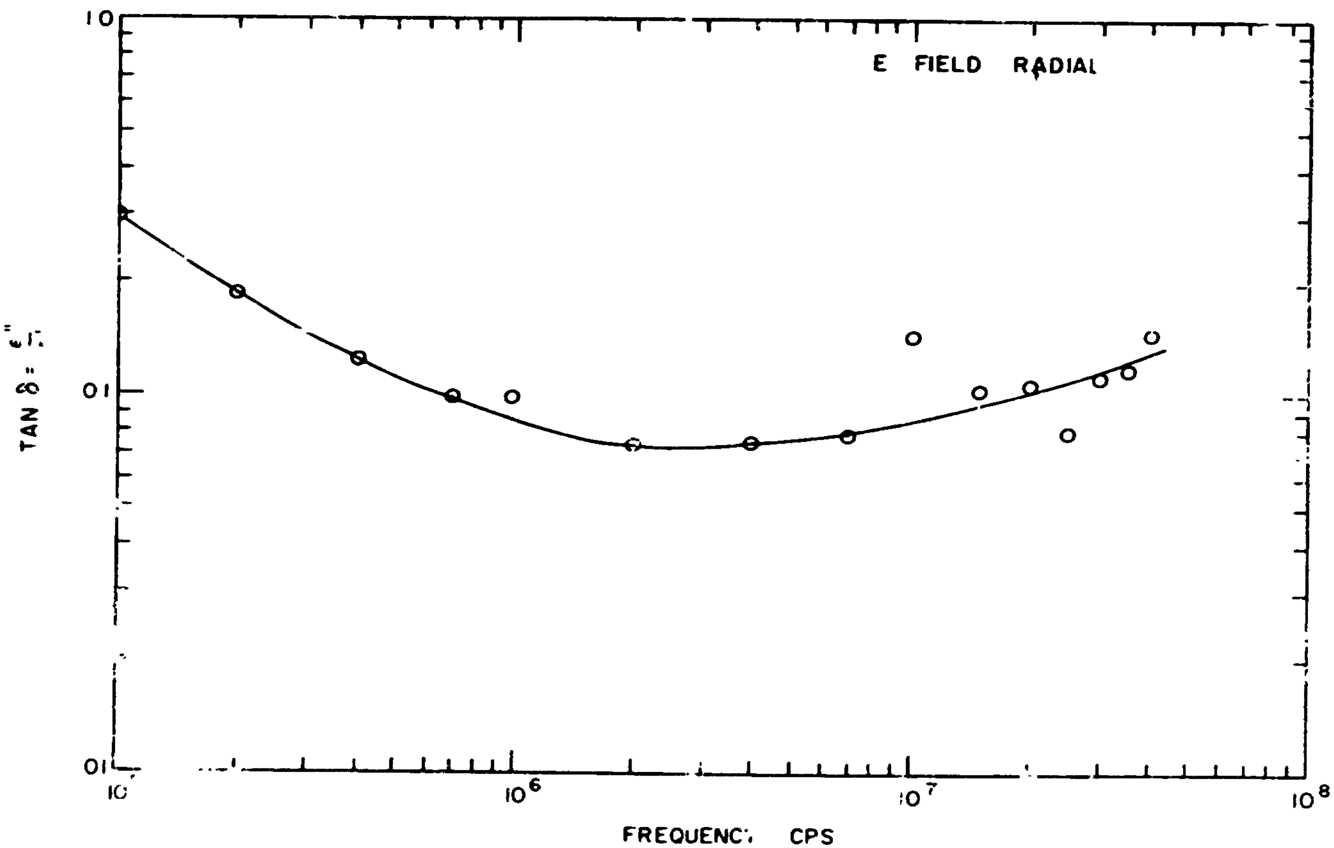
Dielectric measurements on loblolly pine bark were made and are reported in Figure 11. The method of measurement is described in Appendix C. The results show a decrease in dielectric constant with increasing frequency. The loss tangent curve of the bark (Figure 12) appears to be very similar in shape to a portion of the loss tangent curve for fir wood (96% MC) given by Trapp and Pungs[20] (Figure 10). The measurements on loblolly pine bark were made in a radial direction. It is very probable that results would be different in a longitudinal or tangential direction due to the layer structure of pine bark.

The sample measured was taken from a large loblolly pine in Bastrop State Park, Texas. The sample extended from a tangent to the cambium layer outward about 4/10 of an inch. The measurements were made in February, 1963. It is probable that somewhat different values would be obtained at other seasons, relative humidities, physiological condition of the tree, and weather conditions. For example, measurements on bark immediately after a rain would probably give a higher dielectric constant.



DIELECTRIC CONSTANT OF LOBLOLLY PINE BARK

FIG 11



LOSS TANGENT OF LOBLOLLY PINE BARK

FIG 12

VII. DIELECTRIC CONSTANT OF A MIXTURE

Strictly speaking, the term dielectric constant can be applied only to homogeneous substances. However, the concept of a dielectric constant can be successfully applied to mixtures composed of two or more substances.[21] The dielectric constant of a mixture of several things can be expressed as a function of the dielectric properties of each material in the mixture, the geometric shape of the particles of each material and the proportion of the total volume occupied by each material. Two limiting cases of a parallel plate capacitor with multiple layers will be considered.

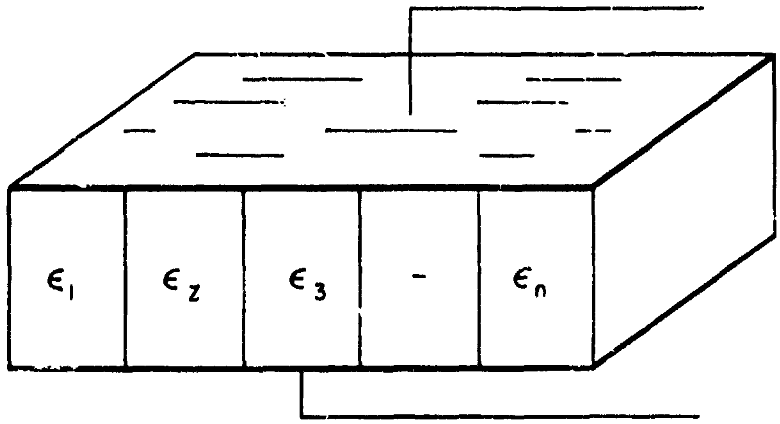
First, suppose the planes of dielectric layers are parallel to the applied E field as shown in Figure 13a. This can be considered as a group of capacitors in parallel. Therefore

$$C_T = C_1 + C_2 + C_3 + C_4 + \cdots + C_n. \qquad (2)$$

But for parallel plate capacitors

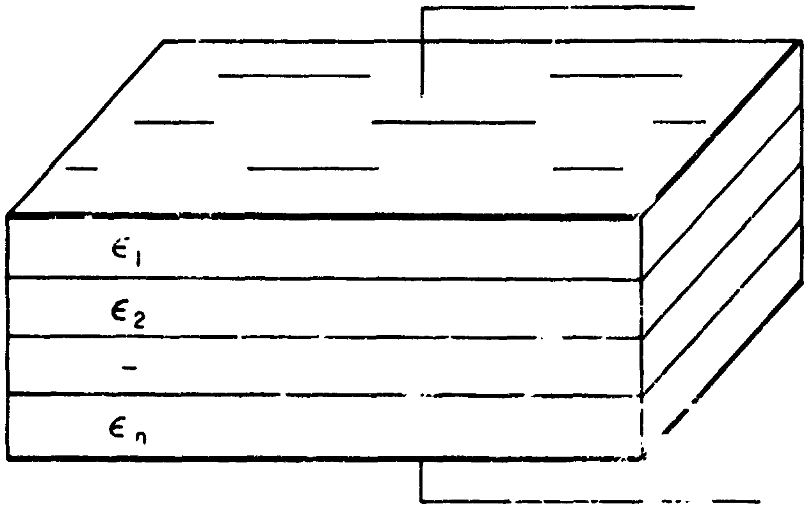
$$C = \frac{K\epsilon_o A}{d} \qquad (3)$$

where
- C - capacitance
- K = dielectric constant
- ϵ_o = permittivity of free space
- d = separation between plates
- A = area of plates



PARALLEL PLATE CAPACITOR WITH
DIELECTRICS IN PARALLEL

FIG 13a



PARALLEL PLATE CAPACITOR WITH
DIELECTRICS IN SERIES

FIG 13b

The above equation can now be written

$$\frac{K_m \epsilon_o A_T}{d} = \frac{K_1 \epsilon_o A_1}{d} + \frac{K_2 \epsilon_o A_2}{d} + \cdots$$

$$+ \frac{K_n \epsilon_o A_n}{d} \tag{4}$$

Multiplying both sides by $\frac{d^2}{\epsilon_o}$ results in

$$K_m V_T = V_1 K_1 + V_2 K_2 + \cdots + V_n K_n \tag{5}$$

where V = volume

Dividing both sides by V_T and letting v_i = per unit volume of slab i gives

$$K_m = v_1 K_1 + v_2 K_2 + \cdots + v_n K_n \tag{6}$$

$$K_m = \sum_{i=1}^{n} v_i K_i \tag{6b}$$

For dielectric layers perpendicular to the field lines, the effective condenser may be considered as made up of a series of parallel plate condensers (Figure 1 b). For this case

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n} \tag{7}$$

as before

$$C = \frac{K\epsilon_o A}{d} \tag{8}$$

thus

$$\frac{1}{\frac{K_m \epsilon_o A}{d_t}} = \frac{1}{\frac{K_1 \epsilon_o A_1}{d_1}} + \frac{1}{\frac{K_2 \epsilon_o A_2}{d_2}} + \cdots + \frac{1}{\frac{K_n \epsilon_o A_n}{d_n}} \tag{9}$$

Multiplying both sides by $\epsilon_o A$ and simplifying gives

$$\frac{V_T}{K_m} = \frac{V_1}{K_1} + \frac{V_2}{K_2} + \cdots + \frac{V_N}{K_n} \tag{10}$$

Dividing through by V_T results in

$$\frac{1}{K_m} = \frac{v_1}{K_1} + \frac{v_2}{K_2} + \cdots + \frac{v_n}{K_n} \tag{11}$$

or

$$\frac{1}{K_m} = \sum_{i=1}^{n} \frac{v_i}{K_i} \tag{11b}$$

In the examples considered in this study, the distributions of particles in the medium are much more complicated than the two simple cases illustrated. However, Wiener[22] has shown that for given v_i's the actual dielectric constant lies between the extreme values given above.

Wiener[22] derived a general equation for mixtures. This set of general equations may be written

$$\frac{K_m - K_n}{K_m + U_m} = \sum_{i=1}^{n-1} v_i \frac{K_i - K_n}{K_i + U_i} \qquad (12)$$

where

K_m = dielectric constant of the mixture

K_n = dielectric constant of the media

K_i - dielectric constant of the different materials scattered throughout the media

v_i = per unit volume of the scattered materials

and

$$U_m = \frac{\sum_{i=1}^{n-1} v_i U_i \frac{K_i - K_n}{K_i + U_i}}{\sum_{i=1}^{n-1} v_i \frac{K_i - K_n}{K_i + U_i}} \qquad (13)$$

and U_i is a parameter determined by particle geometry and orientation for simple cases. U has been given for several common shapes by Wiener[22] and Hartshorn and Saxton.[21] See Table II.

It will be noted that equation (12) reduces to equation (6) when $u = \infty$ and to equation (11) when $u = 0$. For purposes of this study, equation (12) is valid if

TABLE II

Values of U for Use in the Dielectric

Mixtures - Equation (12)

geometrical shape	orientation	U
sphere	<u>any</u>	$2\epsilon_n$
circular cylinder	perpendicular to field lines	ϵ_n
thin discs	random	ϵ_{disk}
needles	random	$1/2(\epsilon_{needle} + 3\epsilon_n)$
layers or laminates	planes of laminate parallel to field	∞
layers or laminates	planes of laminate perpendicular to field	0

1. $$K_n < K_{n-1} < K_{n-2} \leq K_{n-3} \leq \cdots K_1 \tag{14}$$

and

2. $$K_{n-1} \geq \frac{\sum_{i=1}^{n-2} v_i K_i + v_n K_n}{1 - v_{n-1}} \tag{15}$$

Condition 1 can usually be satisfied by careful choice of the order of K_i's. It will be shown later that this condition is also satisfied in the example given. Therefore, the mathematical restrictions are met and formula (12) may be used.

VIII. ELECTRICAL PROPERTIES OF LEAVES

Since no measurements on the dielectric properties of leaves were found in the literature, approximate measurements were made by the method described for the bark of the tree in Section VI.

The high conductivity of the leaves and metal to leaf contact problems made the measurements of questionable value. While the dielectric measurements were not completely successful, they did indicate that for frequencies up to 40 megacycles and probably higher, green leaves act as conductors rather than dielectrics. This conclusion is further supported by the composition of leaves themselves. Water, in which many chemical substances are dissolved, makes up 52% to 78% of the total weight of a green leaf.[6] Apparently, some of these dissolved chemicals radically increase the conductivity of water.

Since the leaves are to be considered as conducting bodies rather than dielectric bodies, the effect of the leaves must be handled by means of artificial dielectric theory. W. L. Kock[23, 24] has developed two types of artificial dielectric which have some of the radio frequency properties of ordinary dielectric materials.

The first type has a refractive index of less than one ($n < 1$) where

$$n = \sqrt{\mu\epsilon} . \qquad (17)$$

The second type of artificial dielectrics is referred to as metallic delay dielectrics and has a refractive index greater than $1 (n > 1)$. Kock[24] describes the basic idea of delay dielectrics as follows:

> The artificial dielectric material which constitutes the delay lens was arrived at by reproducing, on a much larger scale, those processes occurring in the molecules of a true dielectric which produce the observed delay of electromagnetic waves in such dielectrics. This involved arranging metallic elements in a three-dimensional array or lattice structure to simulate the crystalline lattices of the dielectric material. Such an array responds to radio waves just as a molecular lattice responds to light waves; the free electrons in the metal elements flow back and forth under the action of the alternating electric field, causing the elements to become oscillating dipoles similar to the oscillating molecular dipoles of the dielectric. In both cases, the relation between the effective dielectric constant ϵ of the medium, the density of the elements N (number per unit volume) and the dipole strength (polarizability α of each element) is approximately given by
>
> $$\epsilon = \epsilon_0 + N\alpha \qquad (2)$$
>
> (18 in this study)
>
> where ϵ_0 is the dielectric constant of free space.

There are two requirements which are imposed on the lattice structure. First, the spacing of the elements must be somewhat less than one wavelength of the shortest radio wavelength to be transmitted, otherwise diffraction effects will occur as in ordinary dielectrics when the wavelength is shorter than the lattice spacing (X-ray diffraction by crystalline substances). Secondly, the size of the elements must be small relative to the minimum wavelength so that resonance effects are avoided. The first resonance occurs when the element size is approximately one-half wavelength, and for frequencies in the vicinity of this resonance frequency the polarizability α of the element is not independent of frequency. If the element size is made equal to or less than one quarter wavelength at the smallest operating wavelength, it is found that α and hence ϵ in equation 2 (18 in this study) is substantially constant for all longer wavelengths.

Since lenses of this type will effect an equal amount of wave delay at all wavelengths which are long compared to the size and spacing of the objects, they can be designed to operate over any desired wavelength band . . . .

Another way of looking at the wave delay produced by lattices of small conductors is to consider them as capacitative

elements which "load" free space, just as parallel capacitors on a transmission line act as loading elements to reduce the wave velocity. Consider a charged parallel plate air condenser with its electric lines of force perpendicular to the plates. Its capacity can be increased either by the insertion of dielectric material or by the insertion of insulated conducting objects between the plates if the objects have some length in the direction of the electric lines of force. This is because such objects will cause a rearrangement of the lines of force (with a consequent increase in their number) similar to that produced by the shift, due to an applied field, of the oppositely charged particles comprising the molecules of the dielectric material. The conducting elements in the lens may thus be considered either as portions of individual condensers, or as objects which, under the action of the applied field, act as dipoles and produce a dielectric polarization similar to that formed by the rearrangement of the charged particles comprising a non-polar dielectric. Either viewpoint leads to the delay mechanism observed in the focusing action of the artificial dielectric lenses to be described.

Thus, Kock describes the basic principles of artificial dielectrics. Equation (18) for computing the permittivity of an artificial dielectric

is a simplification of Debye's dielectric theory. It will be used in this study and may be alternately written as

$$K = 1 + \frac{N\alpha_e}{\epsilon_o} = 1 + \frac{P}{\epsilon_o E} \qquad (19)$$

where P = polarization per unit volume.

An artificial dielectric affects the magnetic field of a propagating wave as well as the electric field. The magnetic field induces currents in the conducting bodies with the result that the conducting bodies act as magnetic dipoles as well as electric dipoles.[25] The effective permeability of the artificial dielectric is given by the magnetic equivalent of equation (18)

$$\mu = \mu_o + N\alpha_m \qquad (20)$$

This may also be written

$$\mu_r = 1 + \frac{N\alpha_m}{\mu_o} \qquad (21)$$

where μ_o = permeability of a vacuum

N = number of conducting objects per unit volume

α_m = magnetic polarizability of a single object

and μ_r = effective relative permeability of the artificial dielectric.

Since, in this study, the leaves have been assumed to be randomly distributed and all orientations have been assumed to be equally likely, an average contribution to the total dielectric constant by each leaf must be determined.

The average contribution of a single leaf is determined by the following analysis which is a modification of a derivation given by Bottcher.[26] Assume that all leaf orientations are equally probable. Then the number of leaves oriented in a given solid angle is directly proportional to the solid angle enclosed. The expression for a differential solid angle $d\Omega$ is

$$d\Omega = \text{sine}\ \theta\ d\phi\ d\theta \tag{22}$$

Then, the number of leaves (dN) oriented in a differential solid angle will be given by

$$dN = C\ \text{sine}\ \theta\ d\phi\ d\theta \tag{23}$$

where C = a constant to be evaluated.

If equation (23) is integrated over a solid angle of 4π

$$N = \int dN = \int_0^{\pi} \int_0^{2\pi} C\ \text{sine}\ \theta\ d\phi\ d\theta \tag{24}$$

Evaluating (24) and solving for C gives

$$C = \frac{N}{4\pi}\ . \tag{25}$$

Therefore,

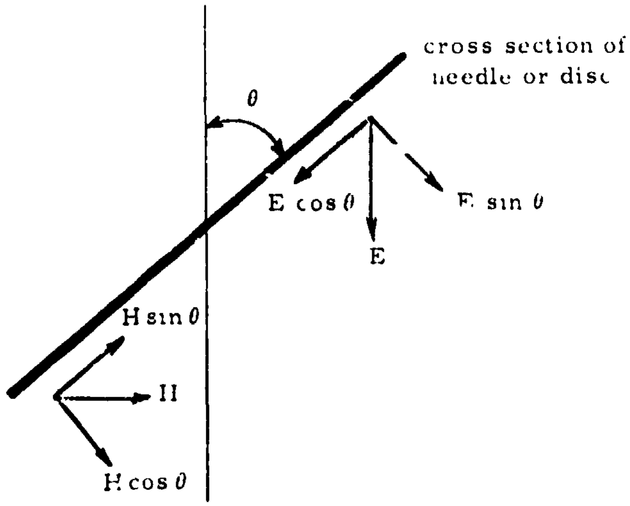
$$dN = \frac{N \text{ sine } \theta}{4\pi} \, d\phi \, d\theta \tag{26}$$

The leaves, however, will be polarized by an external E or H field and will act as dipoles. Since these dipoles will all be set up by an external field rather than being polar molecules to be rotated by the external field, they will be restricted in the θ direction to the range $0 < \theta < \frac{\pi}{2}$ rather than being allowed the full θ range from 0 to π. Taking this factor into account, equation (26) must be modified to

$$dN = \frac{N}{2\pi} \text{ sine } \theta \, d\phi \, d\theta \quad \text{for } 0 \leq \theta \leq \frac{\pi}{2}$$

$$= 0 \qquad \text{for } \frac{\pi}{2} < \theta \leq \pi \tag{27}$$

Equation (27) gives the distribution of leaf orientations to which the polarizing field is applied. The polarizing E or H field may be broken up into two components for disc-shaped and needle-shaped leaves. For leaves shaped like discs, one component is in the plane of the disc and the second component is perpendicular to the plane of the disc. For a needle-shaped leaf one component is along the axis of the needle and the second is perpendicular to the axis of the needle (Figure 14).



Orientation of a leaf with respect to the E and H fields

Figure 14

The net electric polarization (dP) of leaves in a differential solid angle may be written as

$$dP = dN \left[\alpha_{ep}(E \cos \theta) + \alpha_{en}(E \text{ sine } \theta) \right] \qquad (28)$$

where E is the applied electric field intensity

α_{ep} = electric polarizability for E field parallel to the major axis (or parallel to the length) of the object

α_{en} = electric polarizability for E field perpendicular to the major axis (or normal to the length) of the object

dN = number of polarizable objects in a differential solid angle

Since dN is zero over the range $\frac{\pi}{2} < \theta \leq \pi$, the integration is done over a solid angle of 2π instead of 4π. After substituting for dN and setting up the integration

$$P = \int dP = \int_0^{\frac{\pi}{2}} \int_0^{2\pi} \frac{EN}{2\pi} \left[a_{ep} \cos\theta + a_{en} \text{ sine } \theta \right] \text{sine } \theta \, d\phi \, d\theta . \quad (29)$$

After performing the ϕ integration and removing constant terms from the integrals

$$P = ENa_{ep} \int_0^{\pi/2} \cos\theta \text{ sine } \theta \, d\theta + ENa_{en} \int_0^{\pi/2} \text{sine}^2 \theta \, d\theta . \quad (30)$$

But

$$\int_0^{\pi/2} \text{sine } \theta \cos\theta \, d\theta = \frac{1}{2} \quad (31)$$

$$\int_0^{\pi/2} \text{sine}^2 \theta \, d\theta = \frac{\pi}{4} . \quad (32)$$

Therefore

$$P = EN \left(\frac{a_{ep}}{2} + \frac{\pi a_{en}}{4} \right) . \quad (33)$$

From dielectric theory

$$P = (K - 1) \epsilon_o E . \quad (34)$$

Solving for K,

$$K = 1 + \frac{P}{\epsilon_o E} . \quad (35)$$

Substituting equation (33) into equation (35) gives

$$K = 1 + \frac{N}{\epsilon_o}\left[\frac{\alpha_{\epsilon p}}{2} + \frac{\pi\alpha_{\epsilon n}}{4}\right]. \tag{36}$$

By a similar derivation, it can be shown that

$$\frac{\mu}{\mu_o} = 1 + \frac{N}{\mu_o}\left[\frac{\pi\alpha_{mp}}{4} + \frac{\alpha_{mn}}{2}\right] \tag{37}$$

where

α_{mp} = magnetic polarizability for H field parallel to the major axis (or parallel to the length) of the object

α_{mn} = magnetic polarizability for H field perpendicular to the major axis (or normal to the length) of the object

μ = effective permeability of the artificial dielectric.

Schelkunoff[25] and Cohn[26] have given the electric and magnetic polarizabilities of several conducting objects of several shapes. For convenience, some of these have been compiled in Table III. Cautious use of this table is necessary since the polarizability of most objects is different for different orientations of the object with respect to the E and H fields.

TABLE III

Polarizabilities of Conducting Bodies

Shape	Electric	Magnetic
Thin circular rod	$\alpha_{ep} = \frac{4\pi\epsilon \ell^3}{3 \log(\frac{2\ell}{a}) - 1}$	α_{mp} is very small
$\vert\leftarrow 2\ell \rightarrow\vert$ 2a	$\alpha_{en} = 4\pi\epsilon a^2 \ell$	$\alpha_{mn} = -4\pi\mu a^2 \ell$
Thin disc	$\alpha_{ep} = \frac{16}{3} \epsilon a^3$	$\alpha_{mp} = 0$
$\rightarrow\vert 2a \vert\leftarrow$	$\alpha_{en} = 0$	$\alpha_{mn} = -\frac{8}{3} \mu a^3$

IX. METHOD FOR SYNTHESIS OF THE DIELECTRIC SLAB - CALCULATION OF ϵ''

The imaginary part of the dielectric constant is determined by the use of measured attenuation data. This data must be changed from the form of experimental attenuation data to the imaginary part of the dielectric constant. In order to make this conversion certain relations between α, β, ϵ' and ϵ'' must be known.

This study is concerned with plane waves. Since the proposed slab is imperfect, the use of Maxwell's equations for conducting media is indicated. As a result of Maxwell's equations, Ramo and Whinnery[28] give the following formulas for the propagation constant for plane waves in a conducting media:

$$\epsilon_c = \epsilon \left[1 + \frac{\sigma}{j\omega\epsilon} \right] \tag{38}$$

and

$$\gamma = \alpha + j\beta = j\omega\sqrt{\mu\epsilon_c} \tag{39}$$

where

γ = propagation constant

α = attenuation constant

β = phase constant

ϵ_c = complex permittivity of the material

ϵ = real permittivity of the material

σ = conductivity of the material

$\omega = 2\pi f$ = angular frequency

$j = \sqrt{-1}$

The complex permittivity is more commonly represented by

$$\epsilon_c = \epsilon' - j\epsilon'' . \tag{40}$$

Combining equations (38) and (40) and separating real and imaginary parts results in

$$\epsilon = \epsilon' \tag{41}$$

and

$$\epsilon'' = \frac{\sigma}{\omega\epsilon} . \tag{42}$$

Equation (39) may now be rewritten using ϵ'' as

$$\gamma = \alpha + j\beta = j\sqrt{\mu(\epsilon' - j\epsilon'')} \tag{43}$$

Squaring both sides and equating real terms and imaginary terms gives

$$\beta^2 - \alpha^2 = \omega^2\mu\epsilon' \tag{44}$$

$$2\alpha\beta = \omega^2\epsilon'' \tag{45}$$

Solving (44) and (45) for ϵ'' in terms of ϵ' and α gives

$$\epsilon'' = \frac{2\alpha}{\omega^2}\sqrt{\omega^2\mu\epsilon' + \alpha^2} . \tag{46}$$

ε' is determined by using the methods described in the last two chapters. α is determined from an equation given by LaGrone.[29]

$$\text{Attenuation db/meter} = 1.29 \times 10^{-3} (f_{mc})^{0.77} \qquad (47)$$

or

$$\alpha = 1.49 \times 10^{-4} (f_{mc})^{0.77} \text{ nepers/meter} . \qquad (48)$$

This completes the theoretical development.

X. AN EXAMPLE OF THE COMPUTATION OF THE PROPOSED DIELECTRIC SLAB

In order to illustrate the method a complex dielectric constant will be computed for a slab to represent Metz's plot No. 1.[15,16] This plot is described as being 75% loblolly pine and 25% shortleaf pine 25 years of age. The basal area is given as 102.6 square feet total with 102.0 square feet being pine. The remainder is hardwood but will be considered as pine.

The basal area of each species is computed assuming the 75% and 25% to apply.

$$\frac{75}{100} \times 102.6 = 76.9 \text{ square feet basal area of loblolly pine}$$

$$\frac{25}{100} \times 102.6 = 25.7 \text{ square feet basal area of shortleaf pine.}$$

The volume of wood and bark present on the acre will be considered to be directly proportional to the basal area. From Table I at 25 years of age, the basal area of a fully stocked acre is found to be 144 square feet for loblolly pine and 158 square feet for shortleaf pine (from a similar table).

Thus, for wood volume

$$\frac{76.9}{144} \times 3100 = 1655 \text{ ft}^3 \text{ loblolly pine wood}$$

$$\frac{25.7}{158} \times 2400 = \underline{390 \text{ ft}^3} \text{ shortleaf pine wood}$$

$$2045 \text{ ft}^3 \text{ wood}$$

For bark volumes

$$\frac{76.9}{144} \times 800 = 425 \text{ loblolly pine bark}$$

$$\frac{25.7}{138} \times 620 = \frac{101}{526} \begin{array}{l}\text{shortleaf pine bark}\\ \text{total bark ft}^3\end{array}$$

The forest height will be taken to be the weighted average for the two species. Thus,

$$H_f = \frac{75}{100}(56) + \frac{25}{100}(40) = 52 \text{ feet.}$$

The volume of the slab is then

$$V_s = (52)(43,560) = 2.265 \times 10^6 \text{ cubic feet.}$$

The per unit wood and per unit bark for this forest is determined by

$$v_w = \frac{V_w}{V_s} = \frac{2.045 \times 10^3}{2.265 \times 10^6} = 9.03 \times 10^{-4}$$

$$v_b = \frac{V_b}{V_s} = \frac{(5.26 \times 10^2)}{2.265 \times 10^6} = 2.32 \times 10^{-4}$$

The number of leaves per cubic meter will also be taken as proportional to the basal area, thus

$$\frac{76.9}{144} \times 1250 = 66[illegible] \text{ loblolly pine needles per meter}^3$$

$$\frac{25.7}{144} \times 2410 = 430 \text{ shortleaf pine needles per meter}^3$$

Harlow and Harrar[2] give the approximate length of the pine needle as 6 to 9 inches for loblolly pine and 3 to 5 inches for shortleaf pine. Average values of 7.5 inches and 4 inches will be used here.

The cross section of a pine needle is very close to a 120 segment of a circle. For simplicity, this cross section will be approximated by a circle of equal area. Measurements in the laboratory indicate the diameter of this equivalent circle to be approximately .022 inches.

This completes the required statistical data. The computation of the dielectric constant will follow the procedure of considering the dielectric constant resulting from the polarization of the leaves to be the dielectric constant of the media for use in the mixture formula.

By use of the leaf data given above and the formulas of Table III the electric and magnetic polarizabilities are calculated. When the calculations are completed for both species, it is obvious that α_{mp}, α_{mn}, and α_{en} can be neglected.*

Evaluating α_{ep} for loblolly pine

$$\ell = .0952 \text{ meters}$$

$$a = 2.8 \times 10^{-4} \text{ meters}$$

$$\alpha_{ep} = \frac{4\pi\epsilon_o \ell^3}{3 \log_e\left(\frac{2\ell}{a}\right) - 1} = 5.83 \times 10^{-4} \epsilon_o$$

---

*Definitions are given on pages 46 and 48

Considering only the effects of α_{ep}, equation (36) simplifies to

$$K = 1 + \frac{N\alpha_{ep}}{2\epsilon_o}$$

Since two kinds of needles are considered and interaction is neglected

$$K = 1 + \frac{(668)(5.83 \times 10^{-4}\,\epsilon_o)}{2\epsilon_o} + \frac{430\,(1.8\text{r} \times 10^{-4}\,\epsilon_o)}{2\epsilon_o}$$

$$K = 1 + .1947 + .0400 = 1.2347$$

Before the example can proceed further, a frequency of operation and polarization must be chosen. A frequency of 30 megacycles and horizontal polarization is chosen. It is well known that losses will be greater for vertically polarized signals.

Using the dielectric mixture formulas of Wiener[22] the complete dielectric constant can be calculated. From Figures 8 and 11 the dielectric constants are 34 for wood and 2.42 for bark. These values and the per unit volumes calculated* are used in the Wiener formulas presented in the methods chapters. First the wood and bark will be considered as cylinders with axis perpendicular to the E field giving $U = K_n = 1.2347$.

---

*See page 51

Now,

$$U_m = \frac{\sum\limits_{i=1}^{n-1} v_i U_i \dfrac{K_i - K_n}{K_i + K_n}}{\sum\limits_{i=1}^{n-1} v_i \dfrac{K_i - K_n}{K_i + K_n}} \tag{49}$$

Substituting in equation (49)

$n = 3$

$v_1 = 9.03 \times 10^{-4}$ per unit volume

$v_2 = 2.32 \times 10^{-4}$ per unit volume

$K_1 = 34$

$K_2 = 2.42$

$U_1 = U_2 = K_3 = 1.2347$

and evaluating gives $U_m = 1.2347$

Another condition on the use of equation (12) must be checked.

$$K_2 \geq \frac{\sum\limits_{i=1}^{1} v_i K_i + v_3 K_3}{1 - v_2} \tag{50}$$

Substitution in this inequality (50) gives

$2.42 > 1.2$ [illegible] 3.

Therefo . . the computation can proceed. Using the mixture formula

$$\frac{K - K_n}{K + U_m} \sum_{i=1}^{n-1} v_i \frac{K_i - K_n}{K_i + U_i} . \qquad (51)$$

Substituting the values given above in (51) and solving for K gives

$$K = 1.2370.$$

Thus, $\epsilon = \epsilon'' = 1.2370\,\epsilon_o$ farads/meter.

Now using LaGrone's equation (48) for α where $f_{mc} = 30$ megacycles

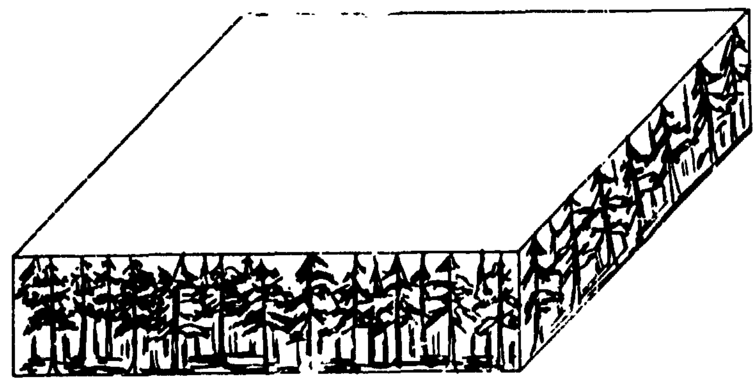
$$\alpha = 1.49 \times 10^{-4} (f_{mc})^{0.77} = 2.04 \times 10^{-3} \text{ nepers/meter}$$

Thus, the complex permittivity of the slab may be written

$$\epsilon' - j\epsilon'' = 1.093 \times 10^{-11} - j\,8.02 \times 10^{-20} \text{ farads/meter}$$

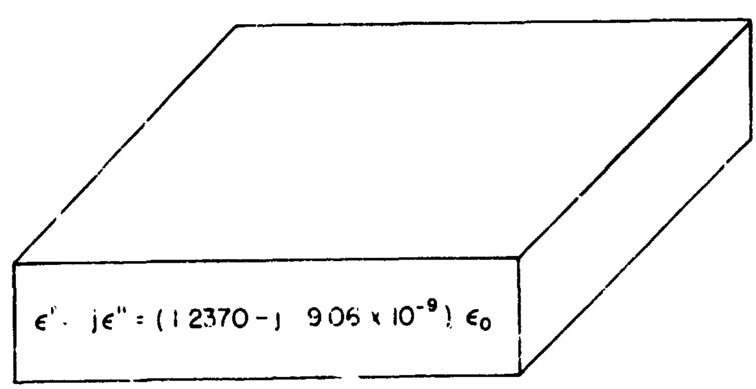
$$= (1.2370 - j\,9.06 \times 10^{-9})\,\epsilon_o \text{ farads/meter}$$

See Figure ·



ARTIST'S CONCEPTION OF METZ'S FOREST
(PLOT NO. 1)

FIG. 15a



DIELECTRIC SLAB REPRESENTATION
OF METZ'S FOREST

(PLOT NO. 1)

FIG. 15b

XI. CONCLUSION

An approximate method for representing a forest by an imperfect dielectric slab has been presented and illustrated by an example. This method is presented as a possible approach to a rather difficult problem rather than as a proven method of solution. The usefulness of the method can only be determined by considerable experimental work.

Several assumptions have been made. Some of the more important ones are:

(1) That dielectric mixture theory is applicable when objects and spacings are both significant in size compared to a wavelength

(2) That the effects of interaction between leaves, and between leaves and the wood and bark are negligible,

(3) That a single smooth topped homogeneous slab can represent a forest,

(4) That leaf placement and orientation are random.

It was necessary to make these and other assumptions in order to circumvent problems brought about by incomplete data in some areas and avoid an excessive amount of involved mathematical manipulations. Some, if not all, of these problems can be solved or mitiga[illegible] by additional work in this area.

Several extensions and refinements are possible in this area

(1) Further testing may show that the tree stems should be considered as conducting bodies rather than dielectric bodies. This would necessitate a different approach to calculating the effects of the wood.

(2) A more accurate dielectric theory which takes interaction between leaves, and possibly between leaves, bark, and wood into account could be applied.

(3) More conductivity and dielectric measurements on leaves could be made to determine more accurately the frequency range in which the leaves may be considered conductive.

(4) Ball[30] suggested that his experiences indicate that pine forests may attenuate signals in the region of 30 megacycles per second more than hardwood forests. Experimental work is needed to determine the significance of Ball's qualitative observations and make possible a more accurate application of the imperfect dielectric slab concept.

(5) It may be possible to approximately evaluate the i^2R loss in a forest and determine whether it is

a significant part of the total signal attenuation by using the imaginary parts of the dielectric constants of wood and bark determined experimentally and the conductivity of the leaves.

(6) More than one dielectric slab or perhaps a dielectric slab whose properties vary with height and location could be used to approximate the forest. One slab, for example, might be used to represent the litter on the forest floor, a second to include the underbrush, a third to include the stem below the crown and a fourth to represent the crown.

(7) Some means of considering the fact that the top of the forest is not flat might be devised.

It would be possible to list even more things but these will suffice to show that much is still to be done.

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D. J. Pounds and A. H. LaGrone
The University of Texas, May 1963

A method for representing a grove of trees by an imperfect slab is developed and illustrated. The method considers leaves as conducting bodies and bark and wood as dielectric bodies using artificial dielectric and dielectric mixture theory to compute the real part of the dielectric constant of the proposed slab. The imaginary part of the dielectric constant of the slab is computed from measured attenuation data. The method is illustrated using data from a real forest to compute the characteristics of an imperfect dielectric slab.

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